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Effect of ionization upon the transition from laminar to turbulent flow in the boundary of a flat plate.

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EFFECT OF IONIZATION UPON THE TRANSITION FROM LAMINAR TO TURBULENT FLOW IN THE BOUNDARY LAYER OF A FLAT PLATE.

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SUMMARY

The purpose of this research was to investigate the effect upon the boundary layer over a flat plate due to ionization of the airstream in the region near the leading edge of the flat plate. The free airstreams of the tests were of low velocities and thus incompressible. The results indicated that ionization of the above portion of the boundary layer caused two distinct improvements over the boundary layer without ionization occurring. The improvements were present for both laminar and turbulent boundary layers, and they were a decrease in the boundary layer thickness and an increase in the boundary layer velocity profile. Although the latter effects were present only in the ionized part of the airstream, they were transferred to the downstream portions of the boundary layer wherein the air was no longer ionized. Therefore, the transition region from laminar to turbulent flow in the boundary layer over a flat plate without ionization was moved downstream when ionization was present in the airstream passing over the upstream part of the flat plate.

EFFECT OF IONIZATION UPON THE TRANSITION FROM LAMINAR TO TURBULENT FLOW IN THE BOUNDARY LAYER OF A FLAT PLATE

INTRODUCTION

The purpose of this research was to examine the effects upon the boundary layer of an incompressible airstream moving over a flat plate when a portion of the airstream in the region of the plate's leading edge was ionized. The effects which were noted were the changes in boundary layer thicknesses and velocity profiles with and without ionization occurring.

Other experiments wherein ionization was utilized as a means of boundary layer control, Ref. 1 and Ref. 2, indicated that ionization of the airstream in and adjacent to the boundary layer brought about decreases in the boundary layer thicknesses and increases in the velocity profiles compared to those without ionization of the air. Both of the above references treated boundary layers which were subject to pressure gradients. This research considered the simpler case where no pressure gradient was present, i. e. an airstream moving over a flat plate. Furthermore, the previous references did not thoroughly investigate the nature of the boundary layer profiles especially laminar and turbulent boundary layer profiles with and without the air being ionized. In this

work both laminar and turbulent boundary layers were examined.

The test data obtained was for low airspeeds, 40 ft./sec. to 82 ft./sec., with ionization of the air below the maximum attainable values. The airflow over the flat plate was considered two-dimensional and incompressible.

The experiments were conducted in the four feet by four feet wind tunnel located in the Oak Street Experimental Laboratories Building of the University of Minnesota. This tunnel had an open throat test section.

Professor John D. Akerman, under whose guidance these experiments were conducted, gave the author the privilege of using the facilities at the University of Minnesota to carry out these experiments. He also gave many helpful suggestions for improvement of the test procedures and equipment. Mr. Frank D. Werner aided immensely in the design of the electrical equipment and in the theoretical phases of gaseous conduction. Professor Newman A. Hall assisted the author in problems which arose concerning the boundary-layer theory. The author is very grateful for the cooperation so generously given by the above men and others of the staff of the University of Minnesota.

METHODS - THEORY

To substantiate the phenomenon due to ionization of the boundary layer of an airstream, existing experimental and theoretical knowledge was employed as a basis. Also to keep the discussion on a plane with both the measurable quantities of the tests contained herein and usable engineering terms, the results of ionization of a gas were given in macroscopic coordinates such as temperature, pressure, velocity, density and viscosity. Thus the problem of what changes took place in the boundary layer of a gas such as air when it was ionized, was attacked from the following two points of view:- ionization of a gas brought about an alteration in the zero slip velocity condition of the gas at the solid boundary or surface of the flat plate; and the viscosity of the gas was changed due to ionization. The above approach to the problem was logical since the resistance of a viscid fluid to a change in shape has been expressed as the shear stress:-

$$\tau = \mu \frac{\partial u}{\partial y}$$

where:- μ = Coefficient of viscosity

u = Velocity of the layer of the fluid parallel to the surface of the boundary or flat plate whose coordinate was x.

y = Distance from the surface of the boundary to the point where u existed.

Experiments have shown that the shear stress effects on the flow patterns of fluids were prominent only in a thin layer of the fluid adjacent to the boundary over which the fluid was flowing. This thin layer has been dubbed the boundary layer. Therefore, any variation in the viscosity, μ, or the value of $\partial u/\partial y$ particularly at the solid boundary would effect the nature of the boundary layer of the fluid. This was made clearer by the following review of existing facts concerning the nature of the boundary layer of a fluid flowing over a solid boundary formed by a flat plate.

The equations which represented the laminar flow part of an incompressible fluid's boundary layer as proven in Ref. 3 and Ref. 4 were (for a flat plate with zero pressure gradient or $\partial p/\partial x = 0$):-

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad \text{(continuity)} \qquad (1)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\mu}{\rho}\frac{\partial^2 u}{\partial y^2} \qquad \text{(momentum)} \qquad (2)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho\, c_p}\frac{\partial^2 T}{\partial y^2} \qquad \text{(energy)} \qquad (3)$$

where:- u, x and y were as given above.

μ = Coefficient of viscosity as above = Constant

k = Thermal conductivity of fluid = Constant

ρ = Density of fluid = Constant (incompressible)

c_p = Specific heat of fluid at constant pressure = Constant

T = Absolute temperature of the fluid at y.

The previous equations were based on the flow having been two-dimensional. Furthermore, if the Prandtl number, $P_r = \mu c_p/k$, equaled one, then equation (3) could be discarded since it was represented by equation (2). In the case of the fluid in question, air, the value of $P_r \doteq 0.76$ was not too far removed from one to make the previous statement unreasonable. Therefore, equation (3) has been dropped by many investigators and only equations (1) and (2) have been used to obtain equations expressing the flow in the boundary layer over a flat plate. Their results have been given in the next paragraph.

By comparison between formulae and experimental data, expressions have been developed which predict fairly accurately the variation of the velocity in the boundary layer, i.e. u, with respect to the distance downstream along the plate, x, and the distance perpendicular to the plate, y. One such equation for laminar flow in the boundary layer based upon von Karman's momentum equation has been developed in Ref. 5, page 158, equation 142, as:-

$$\frac{u}{U} = 2 (\eta - \eta^3) + \eta^4 \qquad (4)$$

with:- U = Free stream velocity.

$\eta = y/\delta$

δ = Thickness of the laminar boundary layer.

The value of δ also was approximately given by (see Ref. 3, page 90, equation (14.12):-

$$\delta = 5.28 \sqrt{\frac{\mu}{\rho} \frac{x}{U}} \qquad (5)$$

According to Ref. 5, page 626, the value of 5.28 above was replaced by 5.83, which discrepancy was due to the deduction of the point of tangency whereat the value of u very nearly equaled the value of U.

Using equations similar to (1) and (2) and (3) and experimental findings, similar relationships for turbulent boundary layers have been given, Ref. 4 and Ref. 5:-

$$u/U = \eta^{1/7} \qquad (6)$$

$$\delta = 0.37 \left(\frac{\mu}{\rho\ U}\right)^{1/5} x^{4/5} \qquad (7)$$

The criterion determining which of the above sets of equations apply to the boundary layer of a flat plate, has been the nature of the main or free airstream above and ahead of the flat plate. If the airstream was laminar, the boundary layer started out at the leading edge of the plate as laminar in nature and remained as such up to a distance downstream along the plate axis whereat a transition region occurred. The position, character and length of that transition region has not as yet been fully evaluated. The boundary layer downstream of the transition region has been found to be turbulent in character. A turbulent boundary layer has been found to exist over the entire length of the plate if the free airstream impinging on the plate was turbulent.

Equations (4), (5), (6) and (7) were derived using

the condition proposed by duBuat and by Stokes:-

$$V_{(tangential)}^{(rel)} = 0$$

where V = velocity in the boundary layer at the surface of the flat plate, i.e. u = 0 at y = 0 for every x along the plate's surface. The above fact has been shown by countless experiments to be true except for rarefied gases and certain organic liquids whose molecules are very large. Therefore, the particles of a fluid in immediate contact with the solid boundary adhere to it, so to speak, without slipping or in other words, there is a zero slip velocity boundary condition at the surface of the flat plate. This in turn implied that $\partial u/\partial y$ at y = 0 was finite, $(\partial u/\partial y)_{y = 0} = K$.

Any reduction in the value of $(\partial u/\partial y)_{y = 0}$ would result in a decrease in the shear stress. To reduce $(\partial u/\partial y)_{y = 0}$ the value of $V_{(tangential)}^{(rel)}$ would have to be made finite, and the limit would be reached when $V_{(tangential)}^{(rel)} = U$ at the surface of the plate thereby eliminating the boundary layer completely. One possible method of making $V_{(tangential)}^{(rel)}$ finite was to charge the particles of the fluid and then impose a like charge upon the particles of the surface of the flat plate. To charge air a corona discharge could be used thereby creating

negative electrons and both positive and negative heavy ions. The speeds of the electrons have been found to be hundreds of times more than those for either the negative or positive heavy ions. Also for air the results of experiments have shown that there was a preponderance of positive ions over negative ions formed in the corona discharge region. Therefore, the only possible charge retained in an airstream any distance downstream of the corona discharge region would be the predominant positive charge due to the heavy positive ions. Fig. 1 schematically depicted the conditions for uncharged air containing neutral molecules and charged air with positive ions moving along the surface of the boundary or flat plate.

In Fig. 1 the particles of the airstream were shown as minute solid elastic spheres many times smaller than the cavities formed by the crystal structure of the surface of the flat metal plate. This was in keeping with the kinetic theory of gases which considers the gas as made up of hard, elastic spheres all of an equivalent cross-section and moving at random with a velocity, v, which was resolvable along three orthogonal axis. Since all of the air's particles were moving in any direction at random until they collided with another particle to have their path and initial velocity altered, the only particles immediately adjacent to the surface of the boundary were those with their velocities, v, directed negative electrons and then positive and negative heavy ions. The speeds of the electrons were found to be hundreds of times more than those of either the negative or positive heavy ions. Also [illegible] the results of experiments have shown that there was a preponderance of positive ions over negative ions formed in the corona discharge region. Therefore, the only possible source [illegible] an electrode any distance downstream of the corona discharge region would be the predominant positive charge due to the heavy positive ions. Fig. 1 schematically [illegible] the conditions for [illegible] neutral [illegible] and [illegible] with positive ions moving along the surface of the boundary [illegible].

In Fig. 1 the positions of the electrons were shown [illegible] many times [illegible] than the [illegible] formed by the original [illegible] of the surface of the [illegible] metal plate. This was in keeping with the kinetic theory of gases which considers the gas as made up of small, elastic spheres all of it [illegible] and moving at random with a velocity, V, which was [illegible] along their [illegible] axis. When all of the gas's particles were moving in any direction at random until they collided with another particle [illegible] initial velocity [illegible], the only particles immediately adjacent to the surface of the boundary were those with [illegible] velocities, V, [illegible] toward the boundary. Upstream of the flat plate, those particles along with the remainder in the airstream had an additional velocity, U, equal to that of the free airstream in addition to their velocities, v. Thus the velocity U was evident as kinetic energy imparted to the air mass while the velocities of the particles, v's, went into giving the air mass its static pressure.

For the case of the uncharged air made up of neutral molecules, Fig. 1 a, the molecules at the surface of the boundary moved initially into the boundary with velocity v and parallel to the boundary with velocity U. Once the molecules entered the cavities or troughs of the boundary they rebounded from the elastic collisions with a net loss of the velocity U, i.e. U = 0. They in turn upon colliding with the nearest molecules of the airstream changed the resultant velocities v and mainly the forward velocity. The forward velocity after collision was $u<U$ where u equaled the velocity of the boundary layer.

If the airstream contained positive ions and the surface of the boundary was positively charged, the conditions were then equivalent to those shown in Fig. 1 b. The positive electrostatic force field of the surface of the boundary, if of sufficient magnitude, caused the positive ion of the force field to be repelled by the concentrated field of the particles at the crests of the boundary surface. Therefore, the ions did not enter the

cavities and did not loose all or part of their forward velocity, U.

The conditions stipulated in the preceding paragraph would result possibly in making $V_{(rel)\,(tangential)} = U$ at the surface of the flat plate and thereby eliminate the boundary layer provided all of the particles of the airstream were charged, i.e. positive heavy ions. According to page 147 of Ref. 7, the possibilities of ionizing all of the particles of a gas, especially at or near atmospheric pressure, were very unlikely. Thus the airstream in this research work, at almost atmospheric pressure, contained both neutral molecules and positive ions. The positive ions did perhaps have some effect on altering the slip conditions at the surface of the flat plate in the region of the corona discharge. However, due to the high mobility of positive ions they deionize by diffusion very rapidly in air at or near atmospheric pressure, see Ref. 6 page 102. To deionize themselves, the positive ions have to pick up electrons from either the gas or the walls of the confining vessel. Hence, the positive ions when moved in the airstream only a short distance downstream of the region of the corona discharge, rapidly converted to neutral molecules by colliding with the bakelite sides of the box and capturing electrons therefrom.

Ionization of the airstream was also influential

in reducing the viscosity of the airstream containing positive ions. This was shown by considering the viscosity to be given by Sutherland's formula, see Ref. 7, page 184:-

$$\mu = \frac{a\, T^{\frac{1}{2}}}{1 + (C/T)} \tag{8}$$

where:- a = Constant dependent on the gas.

$$C = \frac{-4\, f\,(\sigma)\, T}{m\, v^2} \tag{9}$$

$f(\sigma)$ = Force-field between the particles upon colliding.

<0, an attractive force field wherein the collision cross section was increased.
>0, a repulsive force field wherein the collision cross section was decreased.

v = Velocity of the gas particles

m = Mass of the gas particles.

Although the above equation has been supplanted by others, the values of viscosity given by it have been found to agree closely with experimental values for gases at/or near atmospheric pressures.

Assume that the airstream has been ionized with the value of the temperature of the ionized air equal to that for the un-ionized air, i.e. T = constant. This left the variable C, equation (9), to be examined. Had it been possible to ionize all of the particles of air as positive ions, $f\,(\sigma) > 0$, a repulsive force field existing, the viscosity would have been increased. Yet, the possibility of thereby having $0 < V_{\substack{(rel)\\(tangential)}} \leq U$ at the wall might

have been of sufficient consequence to have caused a net reduction of the boundary layer in thickness and an increase in the velocity profiles. However, experiments have definitely shown that, as mentioned previously, it was impossible to completely ionize every particle of the air under the corona discharge. Furthermore experimental results have definitely proven, Ref. 8, that in a gas consisting of ions and neutral molecules, there was a strong attractive force between the ions and the neutral molecules. In fact neutral molecules clustered around a positive ion to increase the collision cross section and decrease the mean free path of the particles of the ionized air. This in turn according to the kinetic theory, reduced the value of the viscosity. Sutherland's formula derived on the principles of the kinetic theory of gases clearly showed that fact. Hence, the ionized air in the corona discharge region had a lower viscosity than that for the un-ionized air provided the temperatures were the same. Equations (4), (5), (6), and (7) indicated that the reduction of the viscosity in turn lowered the thickness of the boundary layer for ionized air in comparison to un-ionized air.

To summarize, the effects of ionizing an airstream would be twofold:- a decrease in the viscosity and an increase of the slip velocity at the surface of the boundary from zero to some finite value over that for un-ionized air. The ionized airstream would be present only have been of sufficient consequence to have caused a net reduction of the boundary layer in thickness and an increase in the velocity gradient. However, experiments have definitely shown that, as mentioned previously, it was impossible to completely ionize every molecule of the air under the corona discharge. Furthermore experimental results have definitely proven, Ref. 8, that in a gas consisting of ions and neutral molecules, there was a strong attractive force between the ions and the neutral molecules. In fact neutral molecules clustered around a positive ion to increase the collision cross section and decrease the mean free path of the particles of the ionized air. This is then according to the kinetic theory, increase the value of the viscosity. Sutherland's formula derived on the principles of the kinetic theory of gases clearly shows that fact. Hence, the ionized air in the corona discharge region has a lower viscosity than that for the un-ionized air provided the temperatures were the same. Equations (9), (10), (6), and (7) indicated that the reduction of the viscosity in turn reduced the thickness of the boundary layer for ionized air in comparison to un-ionized air.

In conclusion, the effects of ionizing an airstream would be twofold: a decrease in the viscosity and an increase of the slip velocity at the surface of the boundary from zero to some finite value than that for un-ionized air. The ionized airstream would be [illegible] in and a very short distance downstream of the region of corona discharge. For a further discussion of the possible factors involved in ionization of moving fluids, see Ref. 9.

EQUIPMENT

The wind tunnel in which the experiment was conducted had an open throat test section, the cross-sectional area of the test section airstream was four feet by four feet. The airspeed in the test section could be varied from 25 ft./sec. to about 100 ft./sec. A view of the equipment mounted in the test section of the tunnel is shown in Fig. 2 and Fig. 3. The speed controls and manometers for registering the tunnel air-pressures is pictured in Fig. 4.

The manometer on the left of Fig. 4 was connected to the static pressure tap vented in four places around the tunnel section upstream of the test section. This manometer had a slant of 28°, and the speed of the airstream was checked by means of it.

The slant manometer to the right of Fig. 4 was of the Rösenmüller type pictured in Ref. 10, page 236, Fig. 199. This manometer was used to measure the difference between the static and impact pressures present in the boundary layer of the flat-plate of the model. The two openings of the manometer were connected - one to the impact tube and the other to the static pressure tap of the

model shown in Fig. 5a and Fig. 5b.

Both of the above manometers contained methyl-alcohol as the measuring liquid.

The model, Fig. 5a and Fig. 5b, was essentially a box with the upper surface acting as the flat plate test surface. All of the sides of the box and the dolly were made from linen-bakelite. There were two flat plates which were interchangeable by means of the screws, one was of brass and the other was of linen-bakelite. Both test surfaces were very smooth. The impact tube consisted of a glass-tube originally 1/8-inch in diameter and drawn down to about 0.044 in. outside-diameter at the end measuring the impact pressures in the boundary layer. The vertical position of the mouth of the impact tube could be varied and measured by means of the graduated pulley which actuated the micrometer head, 0.025 in./revolution. The translatory portion of the micrometer motion was transferred to the glass impact tube via the L-shaped swivel connection. The dolly could be moved in the track to points up and downstream along the plate axis, a set screw fixing it in position.

Four needle points mounted on 1/8-in. diameter screw jacks extended from the brass plate into the region of the airstream at the plate's leading edge. Ionization occurred between the needle points and the brass plate.

Previous attempts at ionizing the moving body of

air were made by means of the network of crossed wires shown in Fig. 2. The wires were of piano-wire of 0.009-inch diameter each spaced 1/8-inch apart, those running horizontally being separated by about 3/4-inch from those in the vertical direction. The horizontal bank of wires covered a vertical distance of 8-inches, the vertical bank - a distance of 4-inches, which meant that the net area where they crossed was 4 by 8 inches. The four nylon lines, - two crossing each of the banks of wire, were used to pull the outer wires of each bank away from each other. This helped cut down the concentration of ionization along the edges of the rectangular area where the wires crossed and cause it to be distributed more evenly over the interior.

Ionization was effected by a half-wave rectified 15,000 volt - 60 milliamp AC power supply. The high voltage leads were easily connected to either each of the banks of wires mentioned above or to the flat plate test surface and the terminal to the plate holding the needle points. The output voltage of the power supply could be varied by the 0-130 volt and 5 amp variac in the input side, see Fig. 6a and Fig 6b for details of the electrical circuit.

A large copper wire mesh screen was placed between the test section opening and the working area outside of test section, see Fig. 3. This screen was intended as a safety feature and was grounded.

TEST PROCEDURE

Initial tests were made with the wire screen of Fig. 2 in position and connected to the high voltage power supply so that ionization was occurring between the crossed piano wires. Pitot surveys were taken in the boundary layer at various points along the flatplate axis with and without the ionization occurring in the rectangular area of the screen. No appreciable effect was noted on the boundary layer velocity profile due to ionization. This fact coupled with the evidence that the ionization occurring between the wires was rather low and concentrated at points within the area rather than being distributed over the area, led to the elimination of this method of ionizing the airstream in favor of the needle points and plate. For the ionization between the crossed wires both the brass flat plate test surface and the linen bakelite plate were tried. Also a high positive voltage of about 1,500 volts was placed on the brass plate. None of the above setups yielded any results. The intensity of the ionization was determined by looking at the bluish glow between the wires in a darkened room. Closer spacing of the wires increased the amount of ionization but also brought some of the wires close enough so that arc-overs occurred which ruptured the wires and was the reason for some wires being missing from the vertical bank of Fig. 2.

Test Procedure

Initial tests were made with the wire screen of Fig. 4 in position and connected to the high voltage power supply so that ionization was occurring between the crossed piano wires. Pitot surveys were taken in the boundary layer at various points along the flat plate model with and without the ionization occurring in the rectangular area of the screen. No appreciable effect was noted in the boundary layer velocity profile due to ionization. This fact coupled with the evidence that the ionization occurring between the wires was rather ill and concentrated at points within the area rather than being distributed over the mesh, led to the elimination of this method of ionizing the airstream in favor of the needle points and plate. For the ionization between the crossed wires both the brass flat plate test surface and the linear beryllium plate were tried, with a high positive voltage of about 4,000 volts applied to the upper plate. None of the above setups yielded any results. The intensity of the ionization was determined by looking at the violet glow between the wires in a darkened room. Closer spacing of the wires increased the amount of ionization but also brought some of the wires close enough so that sparkover occurred which ruptured the wires and was the reason for some wires being missing from the vertical bank of Fig. 4.

All the runs for which the test data was obtained and included in this report, were made with the ionization occurring between the four needle points and the brass plate. Each of the runs consisted of the following procedure. Prior to starting the tunnel, the atmospheric pressure was measured on a mercury barometer and was corrected for temperature. The tunnel was started and maintained at speed by holding the alcohol at a fixed level in the slant manometer to the left on Fig. 4. The micrometer had been adjusted prior to starting so that the glass impact tube head was on the surface of the flat plate,- the dolly having been set at the desired point along the axis. In every run the impact tube was moved away from the surface of the flat plate thereby eliminating any differences in vertical distances due to play in the mechanism had the reverse direction been used. The impact tube was set at successively increasing distances away from the plate by readings on the graduated pulley actuated by a string leading outside of the tunnel. At those distances the value of the pressure registered by the slant manometer shown to the right on Fig. 4 was recorded first for zero-voltage between the needle points and the flat plate and then for approximately 15,000 volts across the above. The run was terminated when the manometer gave successive readings that were constant thereby showing that

the free airstream had been reached. For each distance away from the plate and each corresponding pair of pressure readings the wet and dry bulb temperatures of the tunnel air were recorded along with the temperature of the alcohol in the manometers. The wet and dry bulb temperatures were used to correct the air density of the tunnel air in accordance with the method given in Ref. 1.

A run was made to determine the variation of the static pressure gradient along the plate by connecting tubes to the two static pressure taps on the flat plate, see Fig. 5, and leading them to the slant manometer. The pressure gradient was zero.

An attempt was made to detect whether any ionized air had reached the exit portion of the model by placing a round copper wire screen normal to the airflow downstream of the exit. The edges of the screen had been rounded to eliminate any ground effect between it and the brass plate. The screen was connected to ground through a galvanometer whose sensitivity was about 0.06 microamps per millimeter scale deflection. No reading was obtainable.

TEST DATA

The experimental results indicated that the boundary layer was decreased for both laminar and turbulent flow in the layers, see Fig. 7 and Table I and Table II. As explained above if the free stream was laminar, the

boundary layer would eventually change from laminar through a transition region to turbulent flow. According to the brief resume of the problem as mentioned in Ref. 5, page 325, the exact characteristics of that transition regime have not been clearly established. However, if the pressure gradient over the flat plate was zero, the free stream velocity remained constant and yet by some means the boundary layer was decreased, then it can be stated a' posteriori that the transition region moved downstream and the oscillating point where transition started did likewise. Thus if ionization decreases both the laminar and turbulent boundary layers then it should move the transition point from laminar to turbulent flow in the layer, downstream of the one for no ionization. This was the best approach considering the complexities of the problem of making measurements of the transition region.

Originally the plans were to take successive surveys of the velocity profiles of the boundary layer at points parallel to the axis of the plate. The plate was designed so that it was long enough to initiate transition from laminar to turbulent flow in the boundary layer. During one set of runs, Table I and Fig. 8, when the screen of piano-wires was left upstream of the model, the power supply developed a burn-through in the co-axial high tension leads which dropped the voltage at the needle points to a value whereat no ionization was attained. Those boundary layer would eventually change from laminar through a transition region to turbulent flow. According to the brief summary of the problem as mentioned in Part I, page 259, the exact characteristics of this transition region have not been clearly established. However, if the pressure gradient over the flat plate was zero, the free stream velocity remained constant and yet by some means the boundary layer was disturbed, then it was to be expected theoretically that the laminar region would [illegible] and the [illegible] point where transition started [illegible]. Thus if [illegible] developed with the laminar and turbulent boundary layers then it should move the transition point from laminar to turbulent flow in the layer, [illegible] of the [illegible]. This was the case [illegible] considering the complications of the problem of making measurements of the transition region.

Originally the plans were to make extensive surveys of the velocity profiles of the boundary layer at points parallel to the axis of the plate. The plate was designed so that it was long enough to initiate transition from laminar to turbulent flow in the boundary layer. During one set of runs, Table I and Fig. 8, when the [illegible] of piano-wire was [illegible] of the model, the power supply developed a burn-through in the co-axial high tension leads which dropped the voltage at the sample points to a value where no ionization was attained. These runs provided the only boundary layer profiles which closely resembled laminar layer profiles, see Fig. 7. To ease the operation of adjusting the needle points to the height above the flat plate after they had run for some time and lost some of the metal at the points, the screen of piano wires was removed for the next set of runs, Table II and Fig. 9. The same procedure was followed as for the runs of Table I but the resulting boundary layer velocity profiles were very close to those for turbulent flow even up near the plate's leading edge.

However the main fact evidenced by all of the test data was that the boundary layer with ionization occurring in the region of the leading edge of the flat plate, was improved over that without ionization. By improved it was meant that at constant x and y ordinates in the boundary layer the velocity for the ionization layer more nearly equaled the ideal of the free stream velocity and also that the boundary layer thickness was seemingly lowered in comparison to the un-ionized layer, see Fig. 8 and Fig. 9. From the values of the boundary layer profiles obtained at various stations along the plate, different x's, and for substantially the same free stream velocities of U, the displacement of the profiles for the ionized and un-ionized cases indicated that the ionization effect was occurring upstream in the region of the needle points and the corona discharge. This was in accordance with the

statements made in the section Methods-Theory that the free ions in the airstream downstream of the corona discharge region would lose their charges by quickly neutralizing with electrons captured from the bakelite walls of the model.

Therefore, attention was now confined to the region of the corona or glow discharge at the four needle points. The only means present during the tests for determining the fact that a glow discharge was occurring and for evaluating its intensity was by visually checking the glow in the dark. The effect of the discharge was shown in the photograph, Fig. 10, which was typical of the negative point to plane corona described in Ref. 8, page 515. The glow at the surface of the test plate below each needle point was probably secondary emission. More knowledge concerning the nature of the corona discharge could have been obtained had there been a voltmeter and ammeter in the high voltage side of the power supply. The only possible check on the fact that the glow was at or very near its maximum value was to set the input voltage by means of the variac to a value just below the point whereat arc-over occurred at the points. The reason for not operating the point to plane discharge in the arc-over region was that the amount of free positive ions was reduced, see Ref. 7, page 311. In fact the velocity at a point in the boundary layer was noted to increase when the

corona discharge was present over that without the discharge, but as soon as an arc-over occurred the velocity dropped.

One fact which must be considered was that the air in the corona discharge region was being heated by the interaction between the particles. From previous experiments, see Ref. 7, pages 291 and 313 and Ref. 8, page 607, the temperatures at the needle point and the plate were in the neighborhood of 3,800° F. This in turn meant that the boundary profile undergoing ionization was at a higher temperature than the one for no ionization. Inspection of equations (4), (5), (6), (7), and (8) implied that the boundary layer undergoing ionization should have been thicker and that the velocities lower at corresponding x and y distances compared to the layer with no ionization. (for further information on the effect of temperature upon boundary layers see Ref. 12 and Ref. 13). If temperature had been the only effect on the boundary layer with and without ionization, then the ionization boundary layer velocity profiles at the test points of Fig. 8 and Fig. 9 should have been thicker and contain lower velocities than those for the no ionization profiles. Since the latter was not the case, the only answer was that the ionization brought about a sufficiently large enough change in the boundary layer profiles to offset the temperature effect.

Unfortunately no accurate check could have been

made upon the temperature gradients in the boundary-layer, due to the fact that any thermocouple brought into the boundary layer close to the plate at 15,000 volts would have caused an arc-over to occur between the plate and the thermocouple to make any readings impossible.

According to the findings in Ref. 1, the ionization of the boundary layer obviously had no effect beyond 26 ft./sec. Test results presented as Table III and Fig. 1 were used as a check since it was easier to assume that the turbulent boundary layer profiles obeyed equation (6) rather than try to fit a curve to the laminar boundary layer profiles of Fig. 8 which did not closely approximate equation (4), see Fig. 7. The results of u/U versus η were plotted on Fig. 11 for both the ionized and un-ionized boundary layer profiles measured at x = 8 in. From equation (6) for the same values of x and y, the thickness of the ionized boundary layer, δ_i, was related to the un-ionized thickness, δ, by:-

$$\delta_i = \delta \left[\frac{u/U}{(u/U)_i}\right]^7 .$$

The above equation implied that the ratio of $(u/U)/(u/U)_i$ should have been constant for the ionized and un-ionized layers at equal values of y and U. This condition could not be met by the values of Table III because the amount of ionization occurring at each set of (u/U) and $(u/U)_i$ taken at the same y was not exactly the same. The influence of

leakage through the co-axial cables carrying the high voltage to the model grew worse during each series of runs thereby reducing the amount of ionization during the course of a run. Also from the curves of Fig.11 it was evident that all the values of u/U, $(u/U)_i$ and η did not lie exactly on the theoretical curve. To make a rough approximation of the effect of speed changes upon the results due to ionization the following was done.

For constant U and at each value of y the ratio of $(u/U)/(u/U)_i$ was computed. The seventh-power of each was taken to give the corresponding δ_i/δ. The results were averaged to give:- For $U = 46.1$ ft./sec. $\delta_i/\delta = 0.850$

$U = 61.5$ ft./sec. $\delta_i/\delta = 0.935$

$U = 76.5$ ft./sec. $\delta_i/\delta = 0.947$

Since the effect upon the boundary layer due to ionization occurred in the region of the corona discharge, the decrease in the boundary layer thickness due to ionization could be likened to a decrease in the length of the flat plate from x to x_i. This was determined from:-

$$\delta_i = 0.37 \left[\frac{\mu}{\rho\, U}\right]^{1/5} x_i^{4/5} \qquad \text{(Ref. 3, page 147 equation (23.4))}$$

whence:- $\delta_i/\delta = (x_i/x)^{4/5}$

The above assumed that the ionized and un-ionized boundary layers downstream of the corona had the same values of μ and U and ρ. Since x = 8 in., then:-

for $U = 46.1$ ft./sec. $x_i = 6.54$ in., $\Delta x = 1.46$ in.

$U = 61.5$ ft./sec. $x_i = 7.35$ in., $\Delta x = 0.65$ in.

$U = 76.5$ ft./sec. $x_i = 7.49$ in., $\Delta x = 0.51$ in.

where:- $\Delta x = x - x_i$

From the above values of Δx it may be concluded that the effect due to ionization decreased with increase in airspeed U. However, due to the above mentioned inconsistency in the amount of ionization which occurred during each reading giving $(u/U)_i$ and that the accuracy of the measuring manometer at the higher speeds (which meant higher slant angles for the manometer leg) was not within the accuracy needed to calculate the values of u in the third place, the preceding statement was very questionable. (The accuracy of u/U and $(u/U)_i$ to the third place was very effective when the seventh root was taken to obtain δ_i/δ.) The values of Δx did provide definite evidence that the changes in the boundary layers caused by ionization was confined approximately to the region bounded by the corona or glow discharge.

CONCLUSIONS AND RECOMMENDATIONS

Ionization of a region of an airstream moving over a flat plate decreased the thicknesses of the boundary layers and increased the velocity profiles in the region where ionization was occurring compared to those without ionization. The above was noted whether the boundary layer was laminar or turbulent. Although the alterations of the

boundary layer were present in the region of the corona discharge, they were transferred to the downstream portions of the boundary layer where the airstream was no longer ionized. Thus any decrease in boundary layer thickness and accompanying increase in velocity profile upstream in the ionization region resulted in decreases in boundary layer thicknesses and increases in velocity profiles at points along the plate downstream of the ionization region. Hence, the transition point from laminar to turbulent flow with ionization of the airstream present upstream, was moved downstream from its position when there was no ionization of the upstream portion of the airstream.

From the above conclusions and the fact that the experimental results did not completely answer all of the problems presented by ionizing the boundary layer, other points worthy of further investigation are mentioned below.

One aspect is the improvement of the ionization process. As mentioned before, the airstreams of this investigation had not been ionized as completely as they could have been. This entails the use of higher voltages and different configurations instead of the needle points and plate arrangement, to provide optimum ionization. The device used by C. M. Shaar in his tests, Ref. 2, not only ionized the air in the boundary layer but also was capable of adding velocity to the boundary layer to increase the velocity profiles. The added velocity was in the form of boundary layer were removed in the region of the vortex discharge, they were transferred to the downstream portions of the boundary layer where the flow was as laminar. Thus any decrease in boundary layer thickness and accompanying increase in velocity profile fullness in the suction region resulted in decreases in boundary layer thickness and increases in velocity profile fullness at points along the plate downstream of the suction region. Thus, the transition point from laminar to turbulent flow with suction at the vortices produces upstream, was moved downstream from the position when there was no suction at the upstream portion of the vortices.

From the above conclusions and the fact that the experimental results did not completely account for all of the problems presented by studying the boundary layer, other future array of further investigations are mentioned below.

An attempt at the improvement of the suction process, at additional points, the effectiveness of this investigation has not been limited as completely as they would have been. This entails the use of higher suction volumes and different configurations located at the suction points and plate arrangements, to provide optimum conditions. The device used by A. E. Jones in his work, ref. 8, not only induced the air in the boundary layer but also was capable of adding velocity to the boundary layer to increase the velocity profiles. The added velocity was in the form of an "electric wind". Also in Ref. 2 the fact that a radiating substance plated to the surface of the boundary in an airstream would act as a source of ions, was proposed as a practical solution to the application of the principles to aircraft and missiles. This latter method is particularly inviting from the point that the ionizing source would not heat the airstream as markedly as an electrical discharge mechanism. Thus the deleterious high temperature effects imposed upon the boundary layer in the corona discharge, suffered in this experiment, would be absent.

Boundary layers in air at lower than atmospheric pressures should be investigated since at lower pressures there are fewer particles of the air to ionize thus making it more likely to attain a larger amount of positive ions, and the charged particles of the air retain their charges for longer distances away from the field producing the ionization.

To definitely prove whether the effect of ionization of the air upon the boundary layer is due to the velocity of the airstream being equal to a finite quantity other than zero at the surface of the boundary, a means of measuring the velocities of the boundary layer at the surface of the boundary must be used. In this investigation, the thicknesses of the glass impact tubes prevented any measurements of the boundary layer velocity profiles any closer to the surface of the boundary than 0.017 in. due to

the introduction of capillarity in the impact tube if the tube-opening was smaller, the thickness of the glass walls of the impact tube, and the interference in the airstream between the tube and the solid boundary when the tube was too close to the boundary.

The effect of speed changes upon the influence of ionization in the boundary layer should be examined. However, since the boundary layer normally starts out at zero velocity at the wall and ultimately reaches free stream velocity, ionization effects should still be predominant in the low velocity portions if high speeds adversely effects the phenomenon.

Ionization of air is also dependent upon the amount of dust and water-vapor entrained in the air. Also high intensity ionization of air causes it to dissociate and form other chemical substances such as ozone. The preceding phenomenon may very markedly influence the results brought about by ionizing the boundary layer, and those could be investigated.

REFERENCES AND BIBLIOGRAPHY

Ref. 1 "INFLUENCE OF AN ELECTRIC FIELD ON THE AIR FLOW AROUND A BODY", by Ruchti, O.; Translation No. F-TS-1056-RE (from German), Headquarters Air Material Command, Wright Field, Ohio

Ref. 2 "IONIZATION AND BOUNDARY LAYER CONTROL", by Shear, C. M.; Masters Thesis, Rensselaer Polytechnic Institute, New York; 1947.

Ref. 3 "AERODYNAMIC THEORY", by Durand, W. F.; Vol. III, Div. G; California Institute of Technology, Cal.; 1943.

Ref. 4 Op.cit. Ref. 3 Vol./VI, Div. T.

Ref. 5 "MODERN DEVELOPMENTS IN FLUID DYNAMICS", by Goldstein, S.; Vol. I and II; Oxford University Press, Great Britain; 1938.

Ref. 6 "GASEOUS CONDUCTORS", by Cobine, J. D.; McGraw-Hill Book Co., Inc., New York; 1941.

Ref. 7 "KINETIC THEORY OF GASES", By Kennard, E. H.; Mc-Graw-Hill Book Co., Inc. New York; 1938.

Ref. 8 "FUNDAMENTAL PROCESSES OF ELECTRICAL DISCHARGE IN GASES", by Loeb, L. B.; John Wiley & Sons, Inc., New York; 1939.

Ref. 9 "IONIZATION AS A FACTOR IN FLUID MECHANICS", by Durand, W. F.; Theodore von Karman Anniversary Volume, California Institute of Technology, Cal; 1941.

Ref. 10 "APPLIED HYDRO-AND AEROMECHANICS", by Prandtl, L., Tietjens, O. G. and Den Hartog, J. P.; McGraw-Hill Book Co., Inc.; 1934.

Ref. 11 "AIR DENSITY TABLES", By Boehnlein, C. T. Engineering Experiment Station Technical Paper No. 17, University of Minnesota, Minn.

Ref. 12 "THE TRANSFERENCE OF HEAT FROM A HOT PLATE TO AN AIR STREAM", By Elias, F.; N.A.C.A. TM 614.

Ref. 13 "TEMPERATURE EFFECTS IN A LAMINAR COMPRESSIBLE FLUID BOUNDARY LAYER ALONG A FLAT PLATE", by Emmons, H. W. and Brainerd, J. G.; Journal of Applied Mechanics, Vol. 18, No. 3; 1941.

TABLE I

EFFECT OF IONIZATION UPON LAMINAR BOUNDARY LAYER PROFILES OF A FLAT PLATE

x, (in.)	2		4		6		8	
	u/U							
y, (in.)	V = 0	V=110	V = 0	V=110	V = 0	V =110	V=0	V=110
0.017	0.861	0.870	0.752	0.767	0.686	0.707	0.651	0.677
.019	.870	.884	.763	.780	.703	.735	.655	.680
.021	.895	.905	.799	.815	.745	.765	.701	.730
.023	.915	.925	.830	.845	.771	.795	.723	.751
.025	.928	.935	.842	.856	.800	.817	.741	.766
.027	.935	.945	.865	.879	.817	.835	.761	.791
.029	.950	.956	.889	.900	.847	.865	.779	.805
.031	.960	.963	.904	.915	.860	.878	.801	.824
.033	.969	.975	.916	.926	.875	.893	.820	.847
.035	.974	.978	.927	.935	.886	.905	.834	.856
.037	.980	.980	.941	.950	.895	.909	.854	.873
.039	.985	.988	.948	.954	.901	.906	.866	.884
.041	.987	.990	.956	.960	.910	.921	.880	.900
.043	.989	0.990	.959	.964	.913	.929	.896	.905
.045			.960	.970	.925	.936	.901	.922
.047			.970	.974	.935	.942	.918	.931
.049			.975	.977	.942	.955	.921	.935
.051			.977	.980	.950	.958	.929	.941
.053					.954	.960	.938	.950
.055					.960	.967	.950	.961
.056			.986	.990				
.057					.963	.970	.954	.963
.059	0.996	1.000			.966	.973		
.061			.991	.994	.974	.979	.960	.967
.063					.976	.980		
.065					.980	.984		
.066			.993	.997			.967	.975
.067					.980	.985		
.069					.985	.986		
.071			.996	.996	.990	.991	.971	.975
.076			0.999	0.999			.976	.982
.081							.986	.990
.085	1.000	1.000						
.086							.93[illegible]	.992
.089					.994	.996		
.091							0.995	0.996
.099					.997	0.999		
.101			1.000	1.000				
.109					.999	1.000		
.116							1.000	1.000
.119					0.999	1.000		

Table 1 (con't.)

x, (in.)	2	4		6		8	
	u/U						
y, (in.)	V = 0	V = 0	V=110	V = 0	V=110	V = 0	V=110
0.126		1.000	1.000				
.141						1.000	1.000
.144				1.000	1.000		
.151		1.000	1.000				
.166						1.000	1.000
0.169				1.000	1.000		

Wire screen of piano-wires in place upstream of model during the above tests.

Ionization between brass plate (flat test plate) and 4-needle points.

V = Voltage into low side of power supply for ionization.

x = Distance along flat plate axis measured from leading edge of plate.

y = Distance from flat plate into boundary layer.

U = Free stream velocity

U = 54.3 ft./sec. for x = 2 in.

U = 52.6 ft./sec. for x = 4 in.

U = 52.3 ft./sec. for x = 6 in.

U = 51.7 ft./sec. for x = 8 in.

u = Velocity in the boundary layer at y.

TABLE II

EFFECT OF IONIZATION UPON TURBULENT BOUNDARY LAYER PROFILES OF A FLAT PLATE

x, (in.)	4		8		12		17.5	
	u/U							
y, (in.)	V = 0	V=110	V = 0	V=110	V = 0	V=110	V = 0	V=110
0.022					0.619	0.634	0.550	0.573
.023	0.834	0.845	0.705	0.724				
.024			.725	.741	.630	.645		
.025	.838	.851						
.026			.724	.741	.645	.660		
.027	.850	.864					.590	.608
.028			.724	.741				
.029	.864	.876						
.031			.741	.765	.676	.696		
.032							.625	.641
.034	.876	.889						
.036			.754	.774	.690	.710		
.037							.650	.665
.039	.896	.910						
.041			.759	.785				
.042							.670	.689
.044	.915	.922						
.046			.776	.796	.724	.740		
.047							.680	.698
.054	.935	.945						
.056			.800	.824	.745	.760		
.064	.955	.965						
.066			.815	.843	.767	.782		
.072							.730	.750
.074	.970	.976						
.076			.840	.870				
.084	.982	.990						
.091					.821	.831		
.097							.777	.798
.101			.890	.915				
.109	0.996	0.996						
.116					.850	.874		
.122							.815	.839
.126			.926	.953				
.134	1.000	1.000						
.141					.886	.906		
.147							.849	.870
.151			.960	.970				
.159	1.000	1.000						
.166					.916	.937		
.172							.880	.894

Table II (con't.)

x, (in.)	4		8		12		17.5	
	u/U							
y, (in.)	V=0	V=110	V = 0	V=110	V = 0	V=110	V = 0	V=110
0.176			0.977	0.989				
.191					0.946	0.965		
.197							0.901	0.925
.201			.994	.998				
.216					.970	.981		
.222							.935	.950
.226			0.998	1.000				
.241					0.987	0.998		
.247							0.950	0.953
.251			1.000	1.000				
.266					1.000	1.000		
.272							0.970	0.982
.291					1.000	1.000		
.297							.976	.987
.322							.990	0.995
.347							0.995	1.000
.351			1.000	1.000				
.372							1.000	1.000
0.397							1.000	1.000

Wire screen of piano wires not in place upstream of model during the above tests.

Ionization between brass plate (flat test plate) and 4-needle points.

V = Voltage into low side of power supply for ionization.

x = Distance along flat plate axis measured from leading edge of plate.

y = Distance from flat plate into boundary layer.

U = Free stream velocity

U = 49.0 ft./sec. for x = 4 in.

U = 46.1 ft./sec. for x = 8 in.

U = 45.0 ft./sec. for x = 12 in.

U = 43.0 ft./sec. for x = 17.5 in.

u = Velocity in the boundary layer at y.

TABLE III

EFFECT OF SPEED UPON IONIZATION OF THE TURBULENT BOUNDARY LAYER OF A FLAT PLATE AT x = 8 in.

U, ft./sec.	46.1		61.5		76.5	
	u/U					
y, (in.)	V=0	V = 110	V=0	V =110	V=0	V = 110
0.023	0.705	0.724	0.715	0.717	0.715	0.720
.024	.725	.741				
.025					.722	.725
.026	.724	.741				
.028	.724	.741	.728	.736	.726	.734
.030					.736	.741
.031	.741	.765				
.033			.745	.755	.745	.750
.036	.754	.774				
.038					.759	.766
.041	.759	.785				
.043			.770	.780	.775	.785
.046	.776	.796				
.048					.786	.790
.053			.795	.806	.805	.810
.056	.800	.824				
.063			.823	.830	.830	.835
.066	.815	.843				
.073			.839	.848	.848	.855
.076	.840	.870				
.083			.866	.875	.875	.886
.093			.876	.889	.890	.895
.101	.890	.915				
.103			.898	.910	.914	.918
.126	.926	.953				
.128			.936	.947	.950	.955
.151	.960	.970				
.153			.968	.976	.975	0.983
.176	.977	.989				
.178			.985	0.991	0.995	1.000
.201	.994	0.998				
.203			0.998	1.000	1.000	1.000
.226						
.228			1.000	1.000		
.251	0.998	1.000				
0.351	1.000	1.000				

Wire screen of piano wires not in place upstream of model during the above tests.

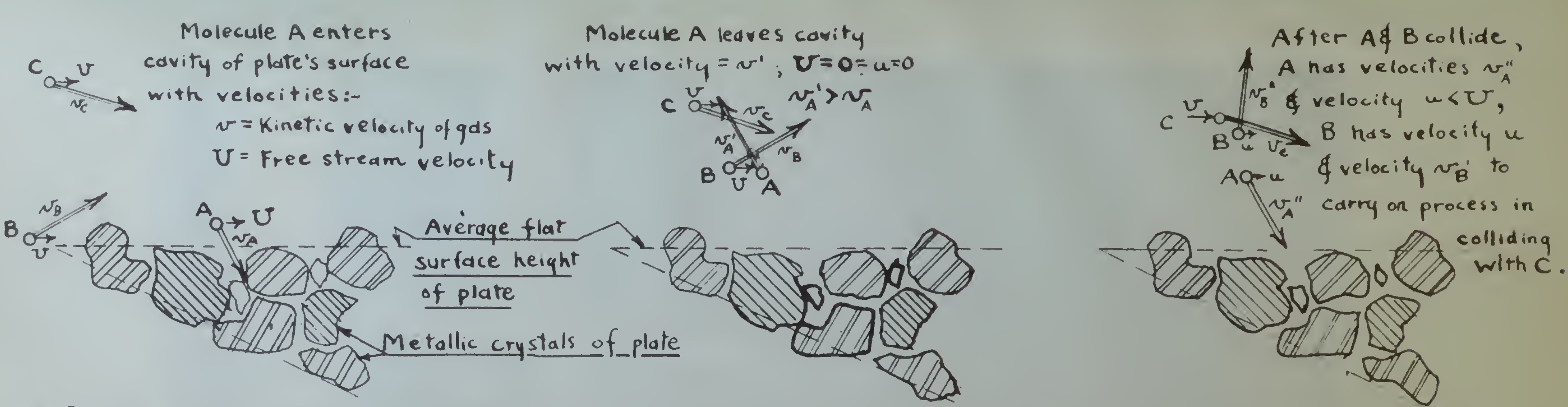
Table III (con't.)

Ionization between brass plate (flat test plate) and 4-needle points.

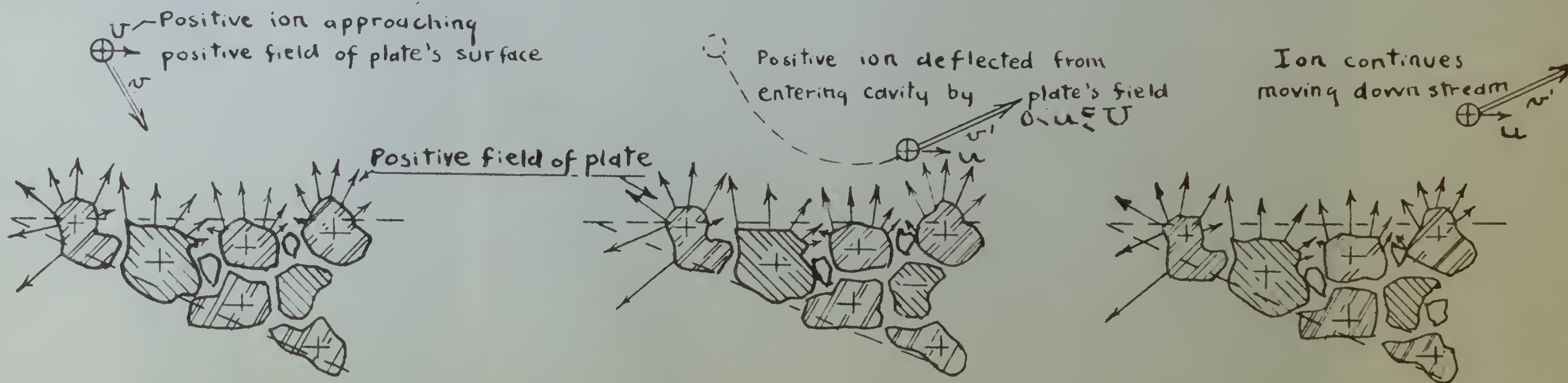
V = Voltage into low side of power supply for ionization.

U = Free stream velocity. u = Velocity in the boundary layer at y.

x and y as on Tables I and II.



a. Progress of molecules in the vicinity of the wall at leading edge of flat plate or downstream.



b. Progress of ion in vicinity of same wall as in a. with wall same charge as ion.

FIG. 1 EFFECT UPON SLIP VELOCITY DUE TO IONIZATION.

U = Free stream velocity ; u = Velocity in boundary layer & at plate surface

Above highly enlarged. Size of surface crystals $\gg$ Diameter of molecules. Ion size > Molecule due to clustering with molecules

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FIG.2 MODEL IN TEST SECTION, PIANO-WIRE SCREEN IN PLACE, UPSTREAM VIEW.

FIG.3 MODEL IN TUNNEL TEST SECTION, DOWNSTREAM VIEW.

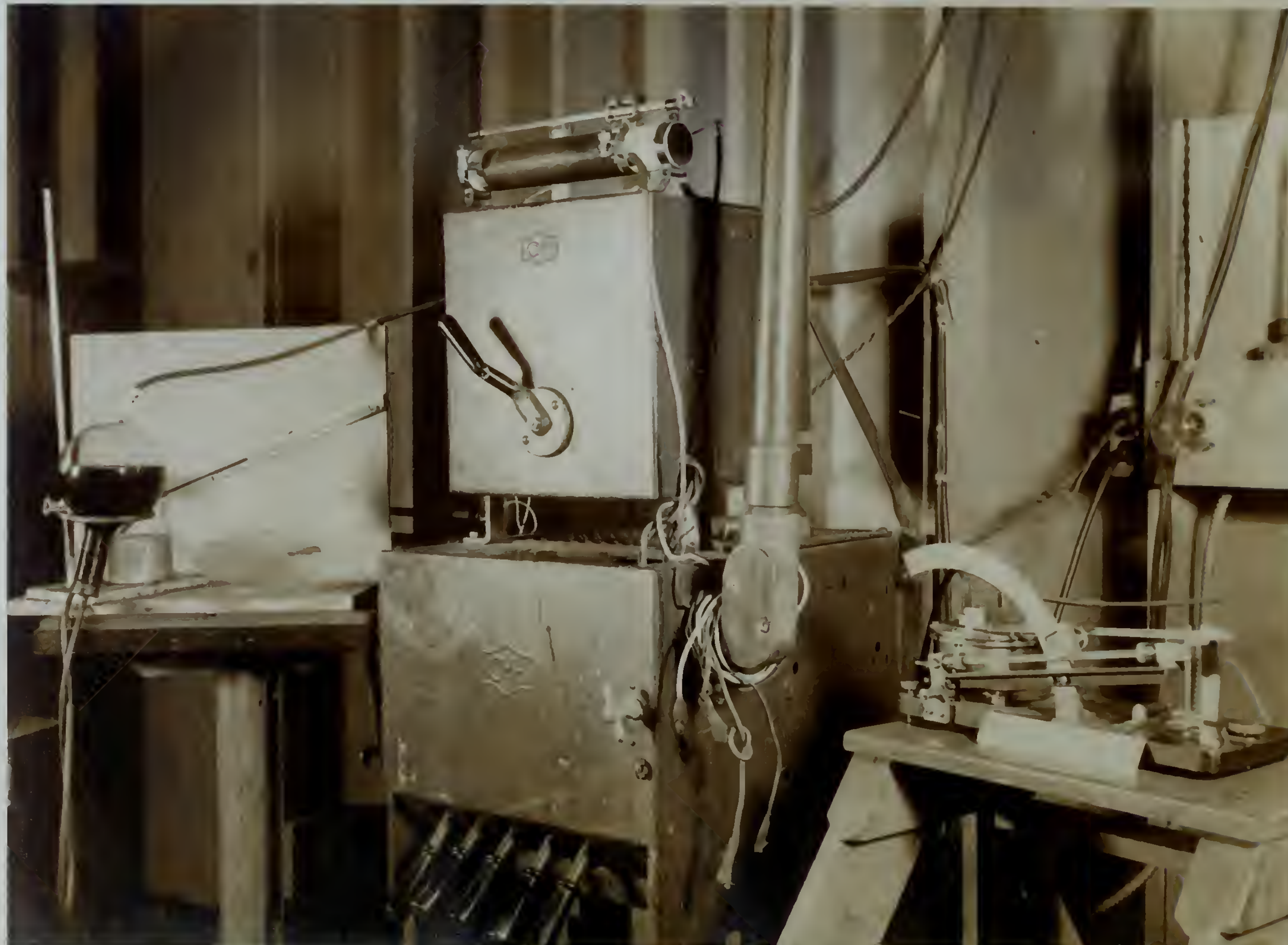

FIG.4 SLANT MANOMETERS & TUNNEL AIRSPEED CONTROLS.

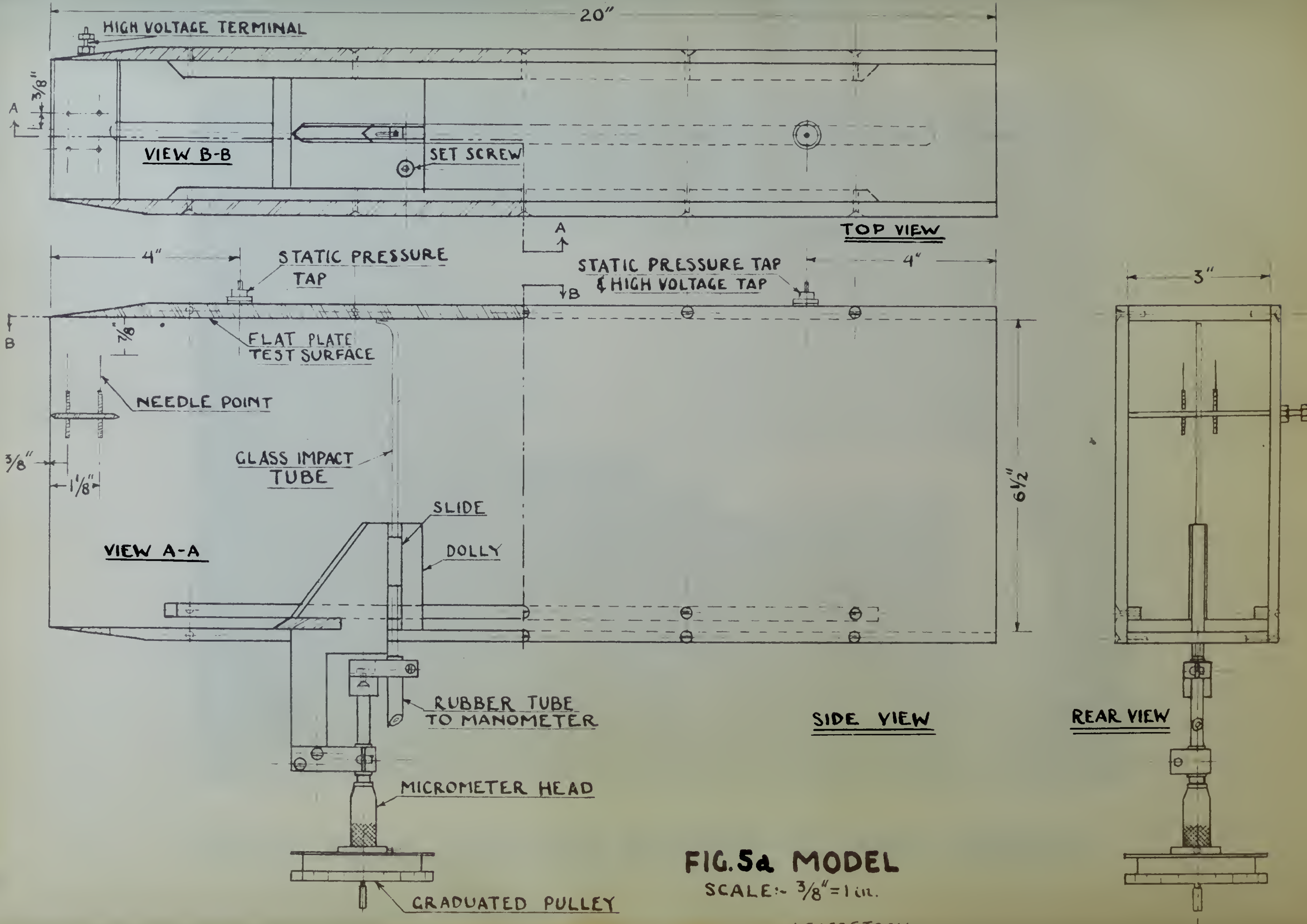

FIG. 5a MODEL

SCALE:- 3/8" = 1 in.

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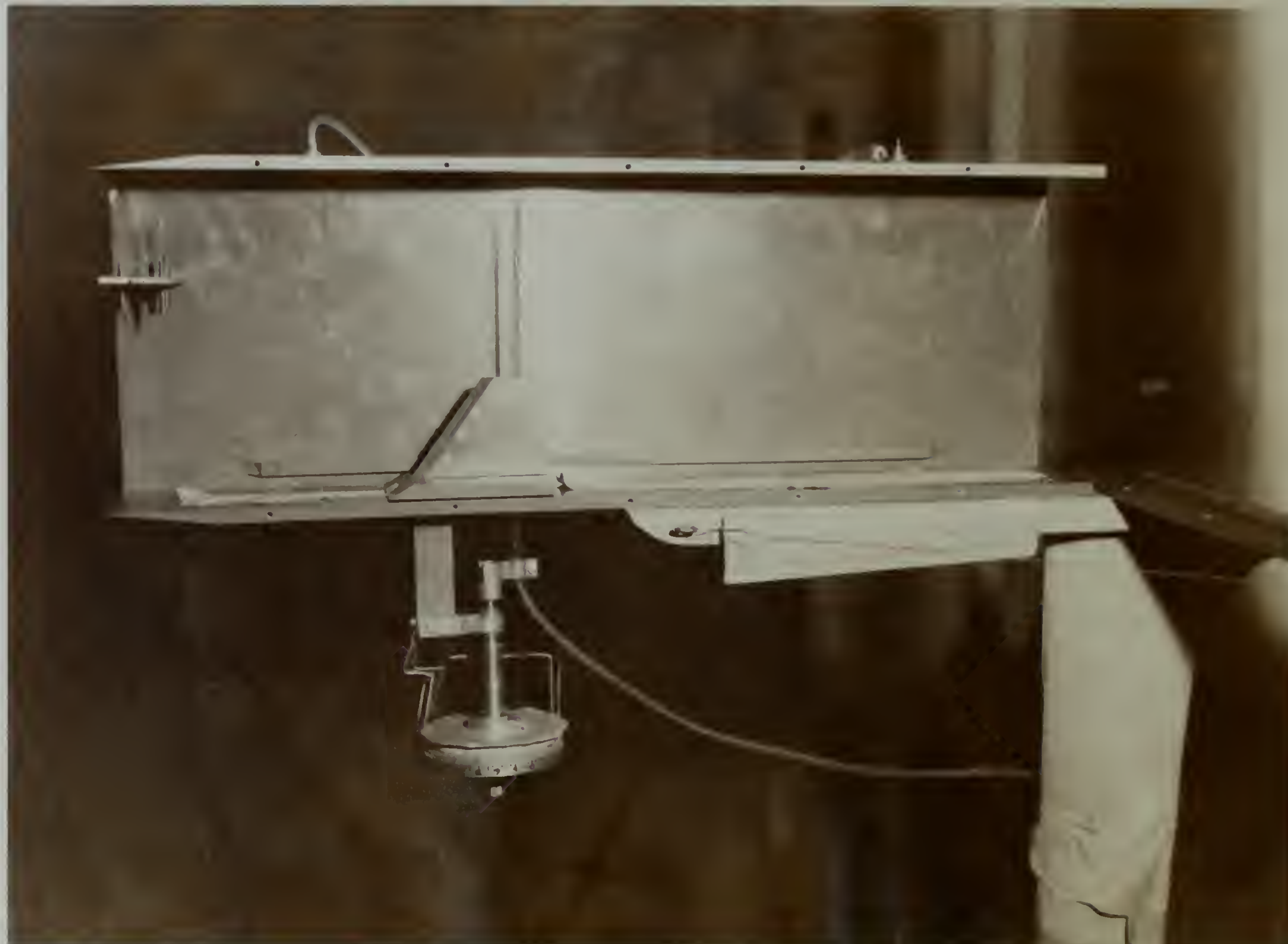

FIG. 5b MODEL, LEFT SIDE REMOVED TO SHOW INTERIOR.

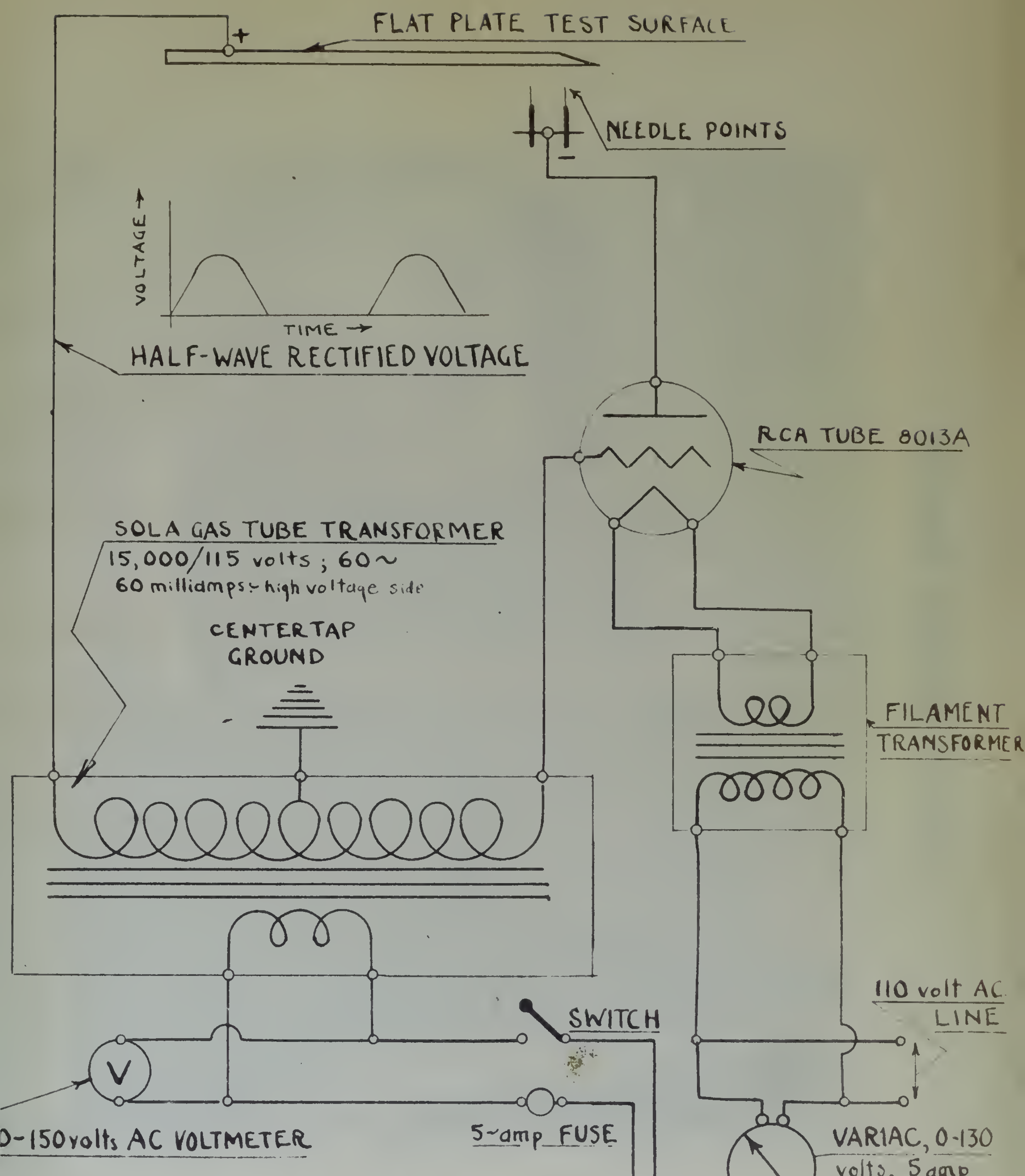

FIG. 6a WIRING DIAGRAM of POWER SUPPLY

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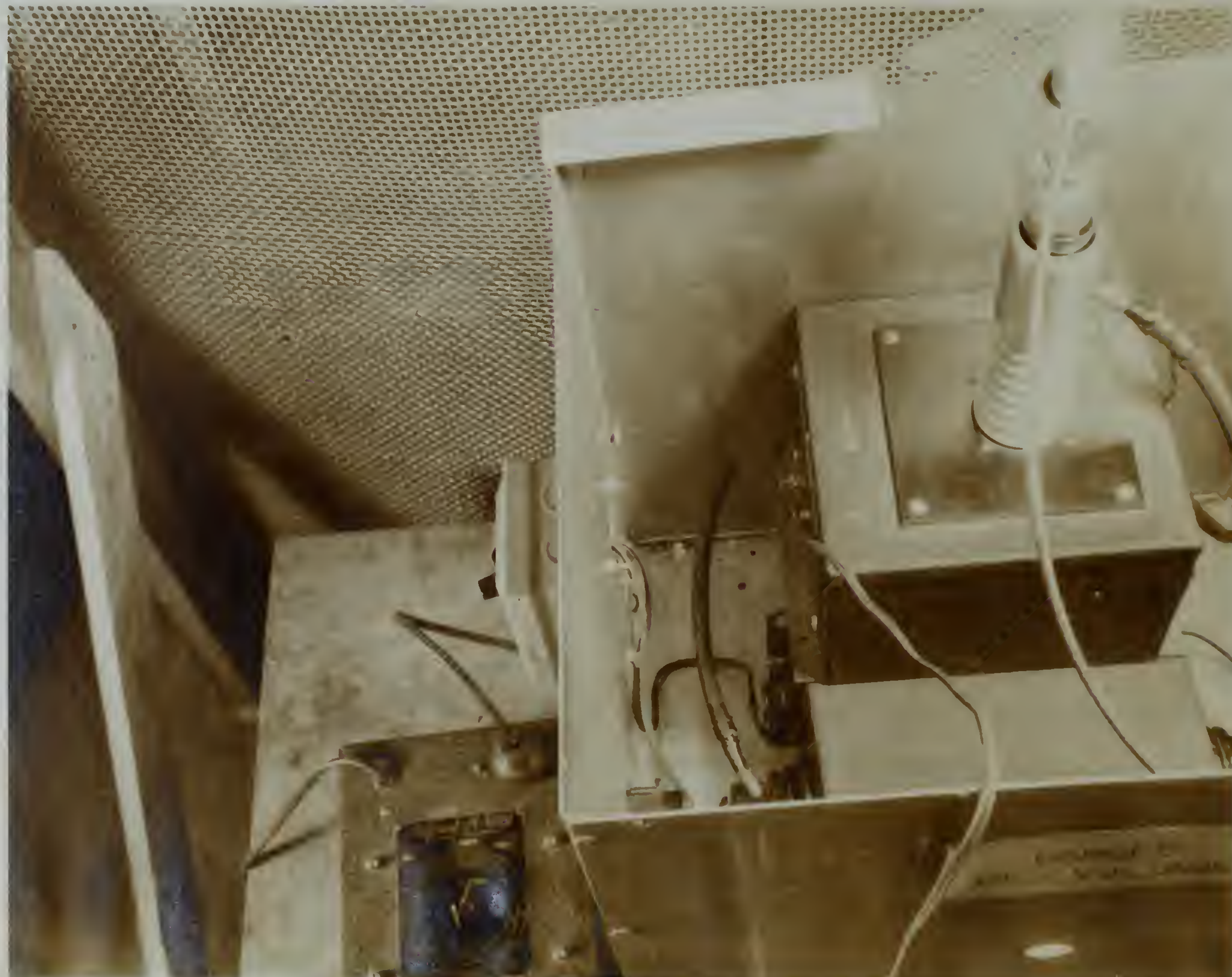

FIG. 6b POWER SUPPLY.

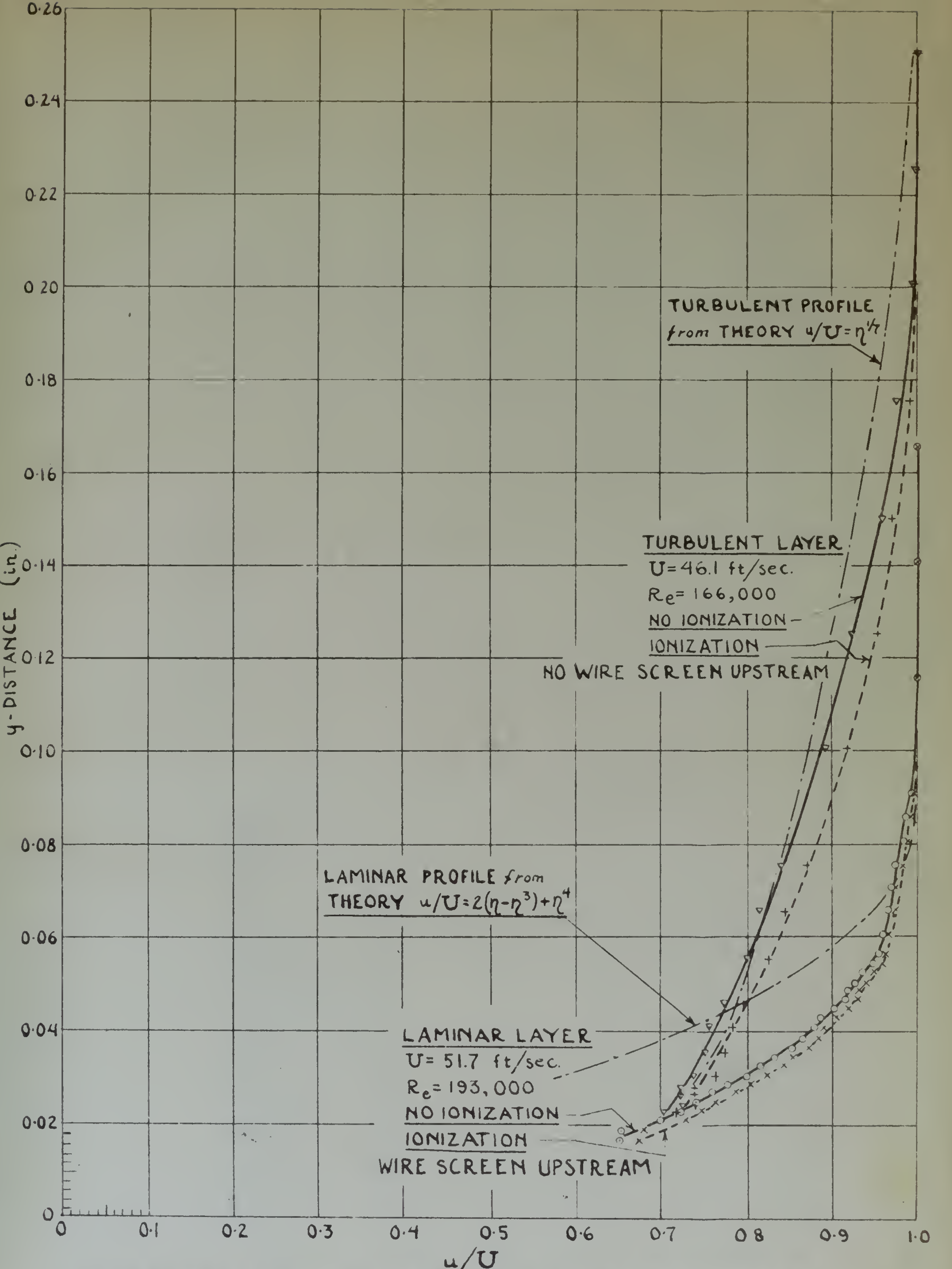

FIG. 7 EFFECT of IONIZATION UPON LAMINAR & TURBULENT BOUNDARY LAYERS @ x = 8 in.

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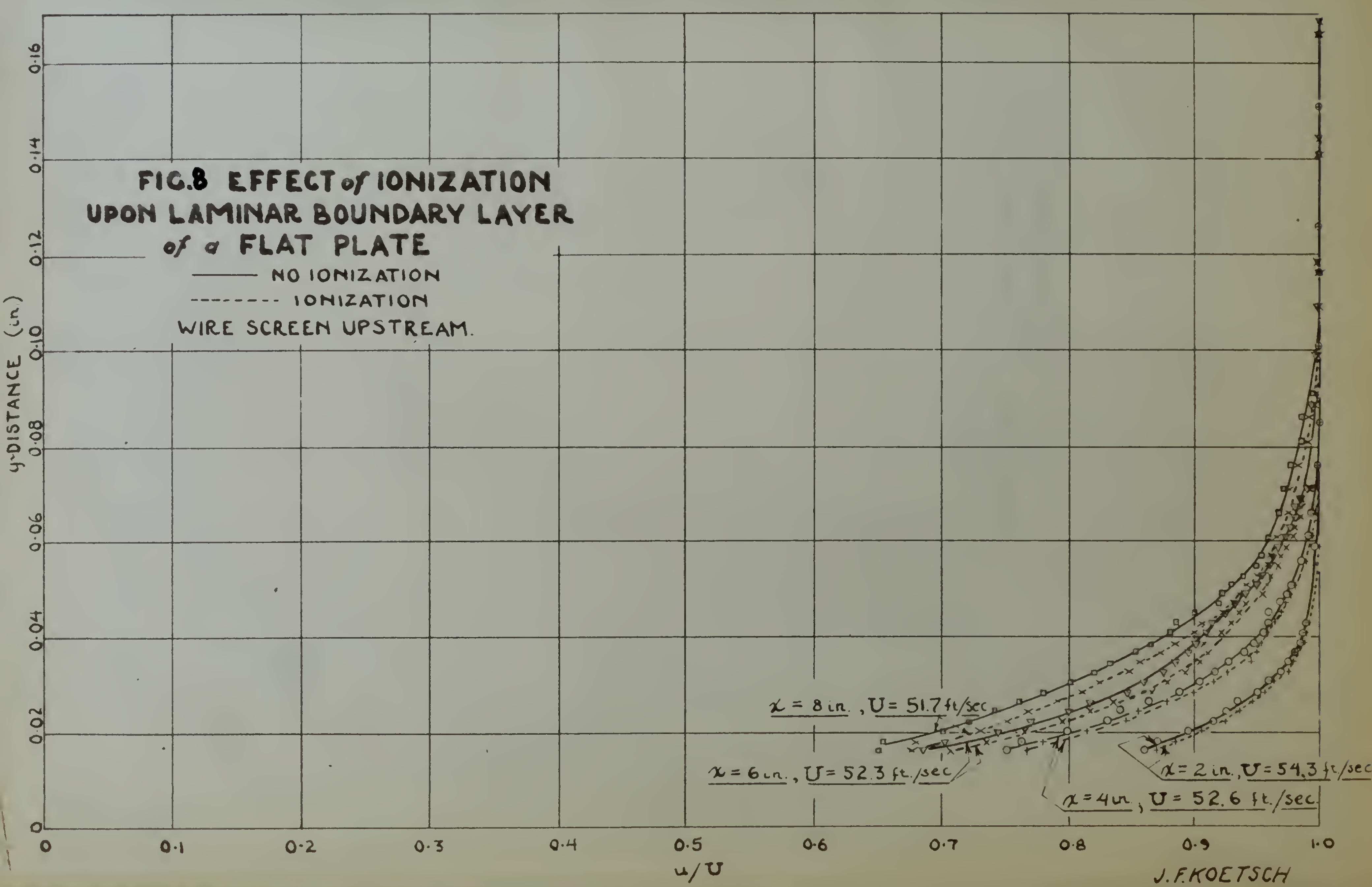

FIG.8 EFFECT of IONIZATION UPON LAMINAR BOUNDARY LAYER of a FLAT PLATE
NO IONIZATION
IONIZATION
WIRE SCREEN UPSTREAM.
x = 8 in. , U = 51.7 ft/sec
x = 6 in. , U = 52.3 ft./sec
x = 4 in. , U = 52.6 ft./sec
x = 2 in. , U = 54.3 ft/sec
y-DISTANCE (in.)
0
0·02
0·04
0·06
0·08
0·10
0·12
0·14
0·16
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
u/U
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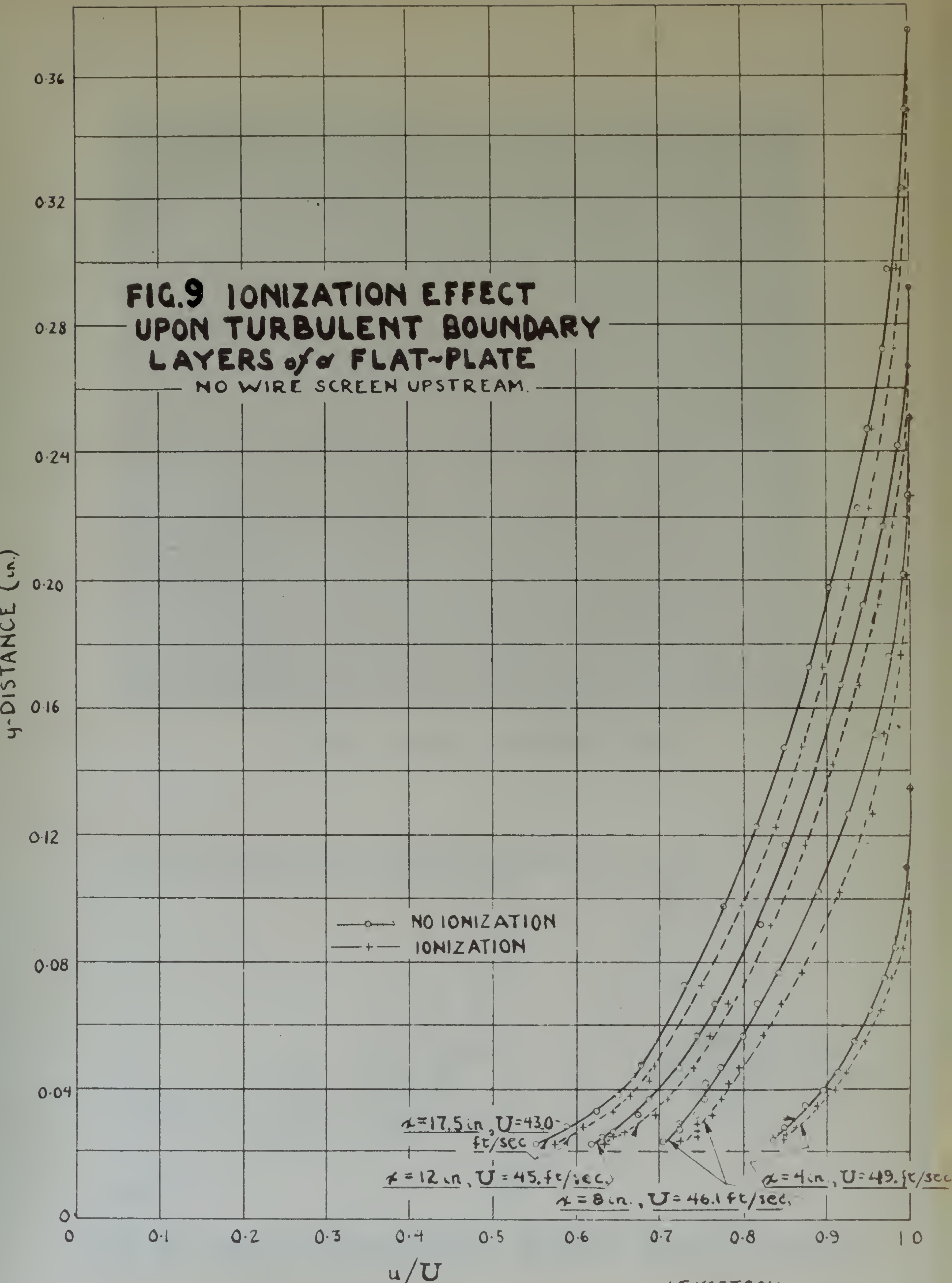

FIG. 9 IONIZATION EFFECT UPON TURBULENT BOUNDARY LAYERS of a FLAT-PLATE

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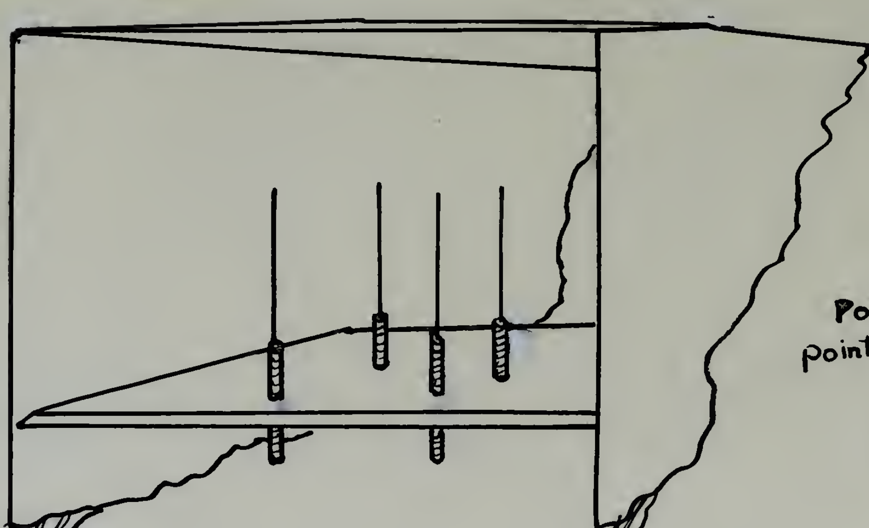
Corona discharge in darkened room.



Positions of needle points & plate in above view.

FIG. 10 CORONA DISCHARGE, NEEDLE POINTS & PLATE.

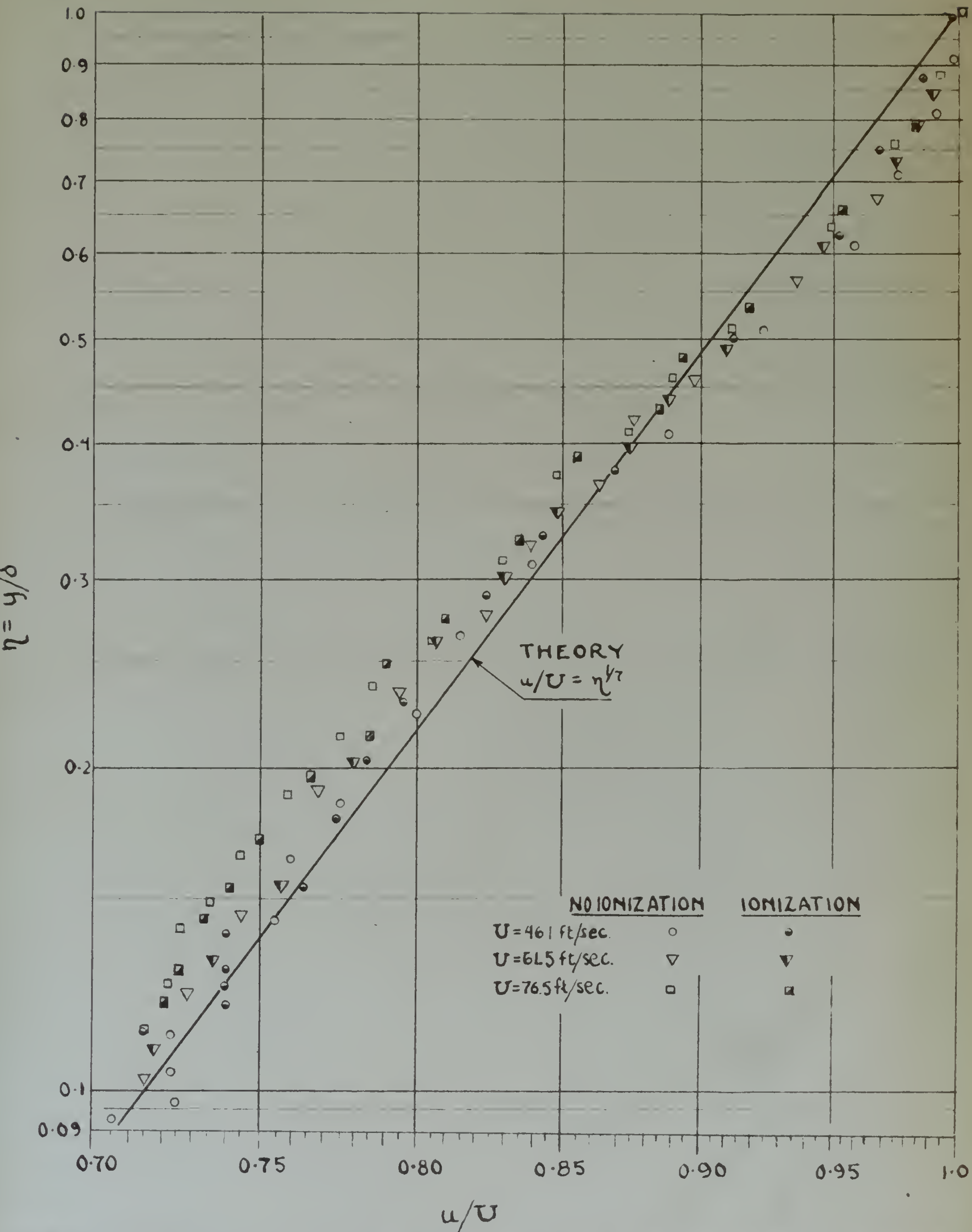


FIG. 11 LOG-LOG PLOT of TURBULENT BOUNDARY LAYERS @ $x = 8$ in. for DIFFERENT AIRSPEEDS, U.

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